Practicalities, pitfalls and new developments in airborne magnetic gradiometry

Scott Hogg, whose company Scott Hogg & Associates, based in Toronto, Canada offers services to the airborne geophysical industry, reviews the latest refinements in the revitalised use of airborne magnetic gradiometers for the mining industry.

The oil and gas exploration industry spurred the development of the first airborne magnetic gradiometers. The motivation was to use Euler's equation with measured vertical gradient to calculate depth to magnetic source. Aeroservice introduced both a helicopter system and a fixed wing towed bird system in the 1960s. Interest in the Euler theory for magnetic analysis was rekindled in the mining industry 20 years later and continues to be the foundation of many new interpretation methods.

In Canada, the GSC developed a vertical magnetic gradiometer in the 1970s. A national mapping programme began in the early 1980s and in response Canadian airborne survey contractors created a variety of fixed-wing and helicopter systems. The mining sector's interest in airborne gradient measurement was based primarily on the increased spatial resolution and detail: small anomalies on the flanks of large features could be clearly resolved. Calculated vertical gradient maps, produced by simple filtering of total field, were found to provide almost the same benefit as measured gradient, at less cost, and the commercial interest in measured vertical gradient faded.

Geometrics introduced a horizontal gradiometer in 1983. This development was of particular significance since, at the same time, they incorporated a technique developed by Nabighian and Hansen to derive a pseudo total field residual from measured horizontal gradients. The demise of the Geometric survey division took horizontal gradients off the horizon for a while. A decade later, this same concept was used by Nelson of the NRC, and more recently implemented in a variety of forms by De Beers and others.

Geodass in Botswana, now Fugro, introduced the first 3-axis gradiometer in the early 1990s. In conjunction with the gradient measurements it provided a variety of compilation and mapping services that made use of the information. In Canada, Terraquest was the first to provide horizontal gradient measurement and Goldak the first to provide a full 3-axis fixed-wing gradiometer. At present, almost all of the airborne contractors offer horizontal gradient systems, and several can now provide full 3-axis configurations for simultaneous vertical and horizontal gradient measurement.

Considerable interest in magnetic gradient measurement has arisen over the past few years. Some of the benefits of gradient are well founded and some are overstated and many are poorly understood. Magnetic gradient measurements can be used to advantage in interpretation. Vertical gradient maps, analytic signal maps, and a host of Euler based methods all use gradient information. The gradient information for these purposes may be calculated or measured. This review addresses methods that rely specifically on measured, not calculated, gradient. At present there are three such primary applications. The first is the potential to avoid diurnal interference, the second is to correct total field for variations in aircraft altitude, and the third is to make significant improvements in the accuracy and resolution of magnetic maps.

Diurnal variation and gradients

For the past 40 years, the potential of gradient data to avoid diurnal variation has been cited as a motivation to record gradient data. Putting the concept into practice has remained elusive. The concept is simple: the difference between simultaneous magnetic measurements will measure gradient and cancel diurnal variation that would be the same at both sensors. The measured gradients can then be integrated to reconstruct a diurnal free total field.

Any gradient can be derived from a total field map and any gradient can be integrated to create a pseudo total field map. The use of the adjective 'pseudo' reflects the fact that the DC component or constant value is not available in the gradient and in practice, longer wavelengths in general, are below the measurement thresholds of the systems. Weak short wavelength anomalies can also be missed by gradient measurement, simply as a result of inadequate sensitivity and resolution.

The longitudinal gradient is measured in the direction of flight, along a flight line. It is the easiest to conceptualize and can be used to illustrate the diurnal correction concept. If one plots the longitudinal gradient in nT/m on the Y axis and the along line distance in metres on the X axis, the change in total field from one X location to another is simply the change in area under the profile. The illustration (Figure 1) is based on real data collected by a fixed-wing system. The black profile on the bottom panel is the measured total field with a constant subtracted. The blue profile on the same panel is the integrated longitudinal gradient. The blue profile in the top panel is the difference between the measured total

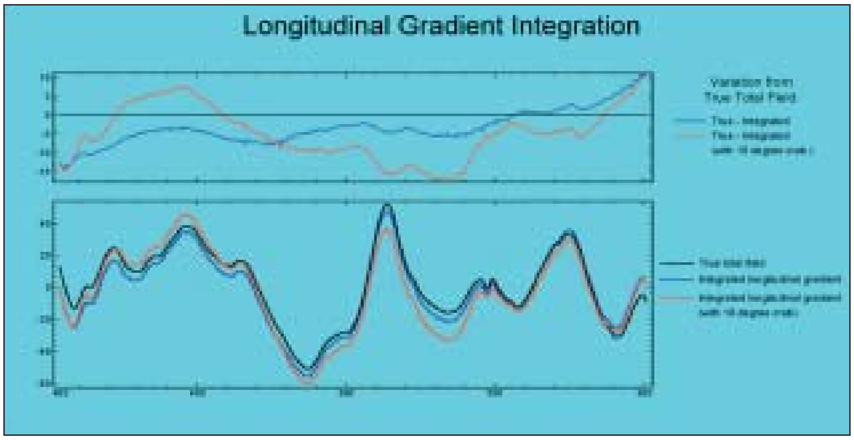

Figure 1 *Longitudinal gradient integration*

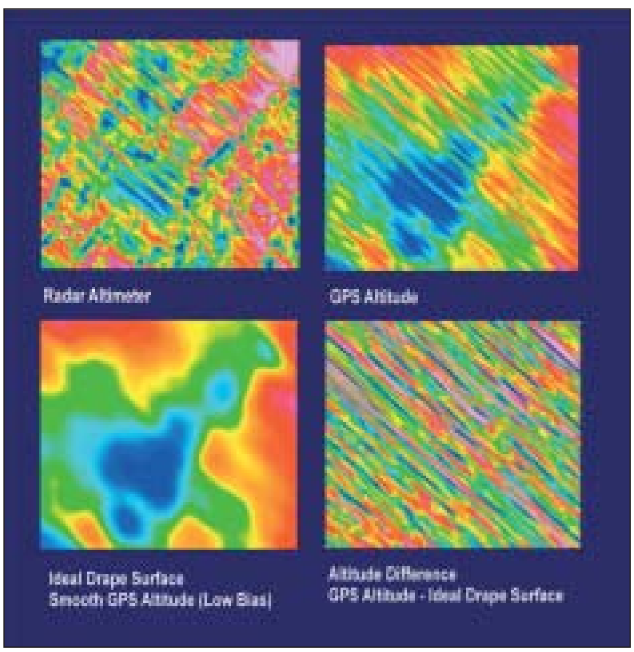

Figure 2 *Survey altitude variation*

field and the integrated longitudinal gradient. Conceptually this difference represents diurnal variation but in practice it may not.

While total field measurements have diurnal as a source of error, gradients measurements may have their own unique sources of error. If there is a cross-wind, the aircraft will crab. The aircraft axis and hence longitudinal gradient will not be aligned in the same direction as the flight line it is following. The red profile is the integrated horizontal gradient that would be obtained with a 10^0 crab angle. This would be the angle for a crosswind of 35 kph at 200 kph along line. The red profile in the top panel is the difference between the measured total field and this integrated longitudinal gradient. The pitfall becomes apparent. While the gradient measurement avoids diurnal interference it has other unique sources of error or uncertainty. Are the long wavelength differences diurnal or simply true total field variations below the measurement threshold of the gradiometer? Are the short wavelength variations diurnal or are they simply due to a sudden crosswind gust?

The illustration here was based on the simple longitudinal gradient but it applies to all measured gradients and all integration techniques. Gradient measurement does provide an independent assessment of possible diurnal variation but practical measurement limitations prevent unambiguous diurnal prediction or avoidance. The point to be made is that integrated gradient is diurnal free but not necessarily error free.

Altitude correction

A practical and proven use of measured vertical gradient is the correction of the measured total field for variations in aircraft altitude. In moderate to rough terrain the differences in terrain clearance from line to line can be significant. This is largely a reflection of an aircraft's ability to descend more quickly than climb. Three dimensional navigation techniques have been implemented that help the pilot follow a smooth drape surface and have been used by the GSC to map some mountainous regions in Western Canada. The practice, while sound, has not been widely adopted by the mining industry perhaps due to the added cost and complexity of the logistics.

Measured vertical gradient measurements can help correct the errors introduced by altitude variations and the method has been used on surveys carried out for the GSC. The example in Figure 2 was taken from a survey over moderate terrain. At the top left is an image of ground clearance as measured by the radar altimeter. At the top right is an image depicting aircraft altitude above sea level as measured by the GPS system. The image at the bottom left is a smoothed version of the altitude above sea-level, biased towards lower elevations. This map reflects what the pilot might have achieved under ideal circumstances and is referred to as the ideal drape surface. The image at the bottom right is the difference in altitude between the ideal drape surface and what was actually flown.

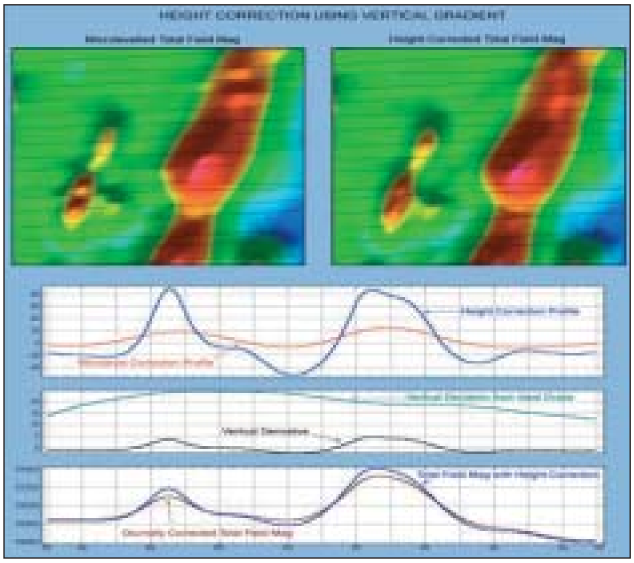

Figure 3 *Effect of altitude correction*

In the bottom panel of Figure 3, the red profile presents the diurnal corrected total field profile used to create the total field map, top left. In the middle panel, the vertical magnetic gradient (black) and the height above the ideal drape surface (blue) are presented. These two profiles can be combined to calculate a height correction that can be applied to the total field. The height corrected profile is shown (blue) in the top and bottom panels. The height corrected profiles produce the total field map shown at the top right. The height correction process has removed some false changes in anomaly shape and amplitude that were due to line to line changes in aircraft height, not geology or diurnal.

This height correction approach can also benefit the levelling or diurnal correction process. If control lines and traverse lines are at different elevations, then the differences in magnetic value reflect height as well as diurnal variation. The upper profile in Figure 4 illustrates a control line magnetic profile together with the crossing traverse line values represented by the rectangles. If there is no difference between traverse and control line values, the rectangle symbols will fall on the zero-line (red). Both traverse and control lines have been corrected in advance by subtraction of base-station variations recorded nearby. The lower profile illustrates the same control and traverse line information after corrections were made for altitude differences. The significant reduction of magnetic differences demonstrates that the original corrections made by base station subtraction were very good and that the apparent residual differences at the intersections were largely due to height differences. Commonly these magnetic variations, due to altitude, are incorrectly attributed to diurnal and micro-level processes are applied that can lead to complex and invalid profile corrections.

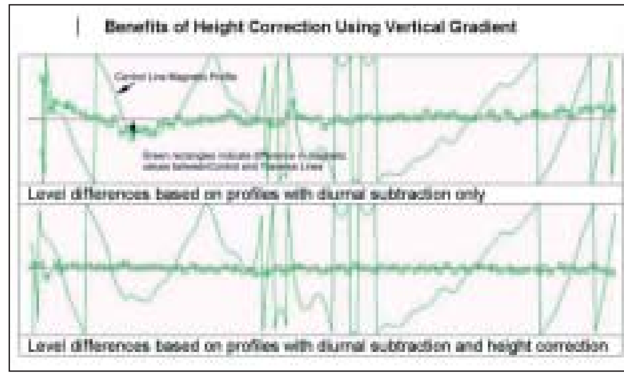

Figure 4 *Height variation and the diurnal correction process*

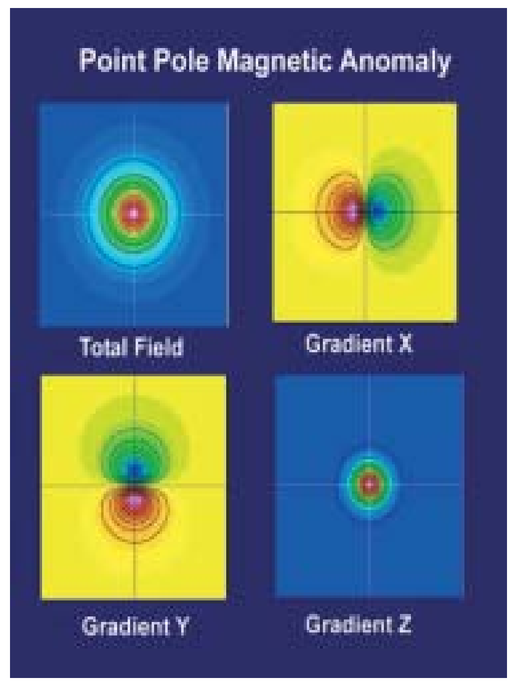

Figure 5 *Point pole magnetic anomaly*

The altitude correction process is relatively simple and can prove very effective, especially in surveys that contain strong magnetic anomalies and high vertical gradients. In such circumstances a slight altitude change can lead to significant total field variation that is very noticeable on the flanks of the strong anomalies. A pitfall of the correction, in the overall gradient context, is that while the total field can be corrected for height variation, the measured horizontal gradients cannot. If the altitude corrections are sufficiently large, the measured horizontal gradients may be no longer valid for the corrected profile.

Improved magnetic mapping

The ability to improve the accuracy and resolution of magnetic maps is one of the greatest benefits of measured horizontal magnetic gradients. To illustrate the concept it is important to understand the nature of the gradients measured. Presented in Figure 5 is the anomaly from a point pole in a vertical magnetic field. The total field, top left, is circular. The vertical gradient, bottom right is also circular but much sharper than the total field. This small diameter reflects the resolving power of vertical gradient that is its main appeal. It also illustrates that flight lines must be very closely spaced to map measured vertical gradient. The horizontal gradients and especially the total field have a larger horizontal footprint than the vertical gradient and thus are somewhat easier to map. The horizontal gradients are presented in the bottom left and top right corners. The red colouring is positive gradient, indicating that the total field peak is being approached in the +X or +Y direction. The negative gradient in blue indicates departure from the peak in the +X or +Y direction.

The point where the horizontal gradients pass through zero is the location of the total field peak. Thus if the flight lines straddle the anomaly and one line records a high and the adjacent line a low; the peak must fall between the lines.

Figure 6 presents the total field and transverse gradient profile over the small point pole anomaly. The horizontal scale is in units of depth, one division equals the height of the aircraft above magnetic source. Note that the distance between positive and negative gradient peaks is roughly equal to the depth. This profile of the TF and gradient response must be sampled by flight lines directed in and out of the page. If the aircraft passes directly over the target we will measure a TF maximum and on the transverse gradient we will measure zero. If the flight line spacing were equal to the depth, say 100 metres altitude and 100 m spacing we would sample this profile at several points. A possible scenario is illustrated for three flight line spacings equal to 1, 1.5 and 2 times depth. The sample points are connected by a linear dotted line and are located to indicate a worst case scenario for flight line placement, which is different for the TF and gradient profiles.

Even in the worst-case line placement scenario, as illustrated here, we are assured of measuring a response. With a line spacing equal to the aircraft height above magnetic source one can expect to measure no less than 70% of peak TF and gradient amplitudes. At a line spacing of 1.5 times depth we anticipate no less than 50% of peak values. At a line spacing of 2 times depth we are assured measurements within about 30% of peak values but are approaching the limits of comfortable detectability. At a line spacing of 3 times depth and beyond it is possible to miss any significant response from a small source between flight lines. This simple model illustrates that detection of even the smallest physical sources can be achieved with a line spacing of up to 2 times height above magnetic source.

Without question, a lower survey height produces higher response amplitudes and sharper detail. However, as illustrated above, a lower survey height must be accompanied by a closer line spacing to maintain a reasonable ratio of 1-2 times height above source. Closer line spacing requires more line kilometres and thus more cost. The difference between 100 m spacing and 150 m spacing can increase the cost of a survey by 50% and anything that can improve mapping performance for a given line spacing will provide a cost-performance benefit. Measured horizontal gradient information can improve the interpolation of data between flight lines and thus increase magnetic map accuracy and resolution without increasing cost.

To make a map it is necessary to interpolate between the flight lines, a process known as gridding. Conventional gridding methods include bi-cubic splines and minimum curvature techniques. Input is a single parameter, TF, measured along profiles. One new method that uses gradient data is the Nelson-Nabighian technique of integrating horizontal gradients. It uses two input parameters, profiles of gradient-east and gradient-north. A version of the process, MagGrad, has been implemented by DeBeers. Another method is gradient tensor gridding, or GT-Grid, developed by Scott Hogg and Associates. This technique uses three input parameters in profile form: TF, gradient-east and gradient-north. Both new processes provide benefits compared with conventional gridding techniques.

The Nelson method is based on a mathematical relationship between vertical and horizontal gradients, developed by

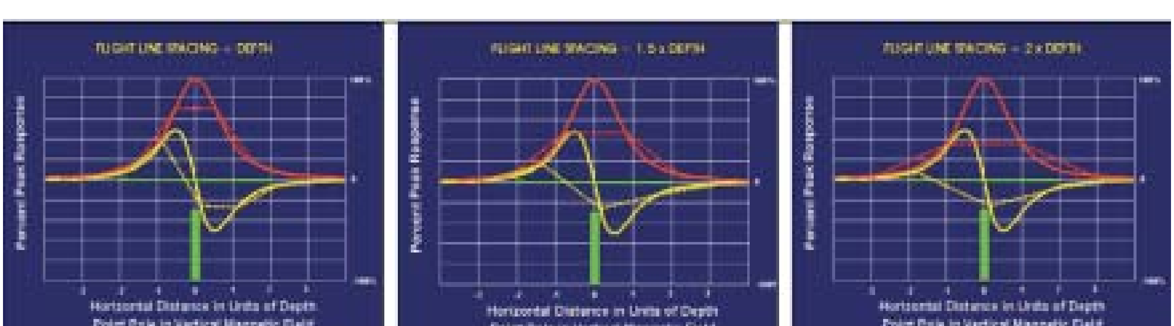

Figure 6 *Flight line spacing considerations over a point magnetic pole*

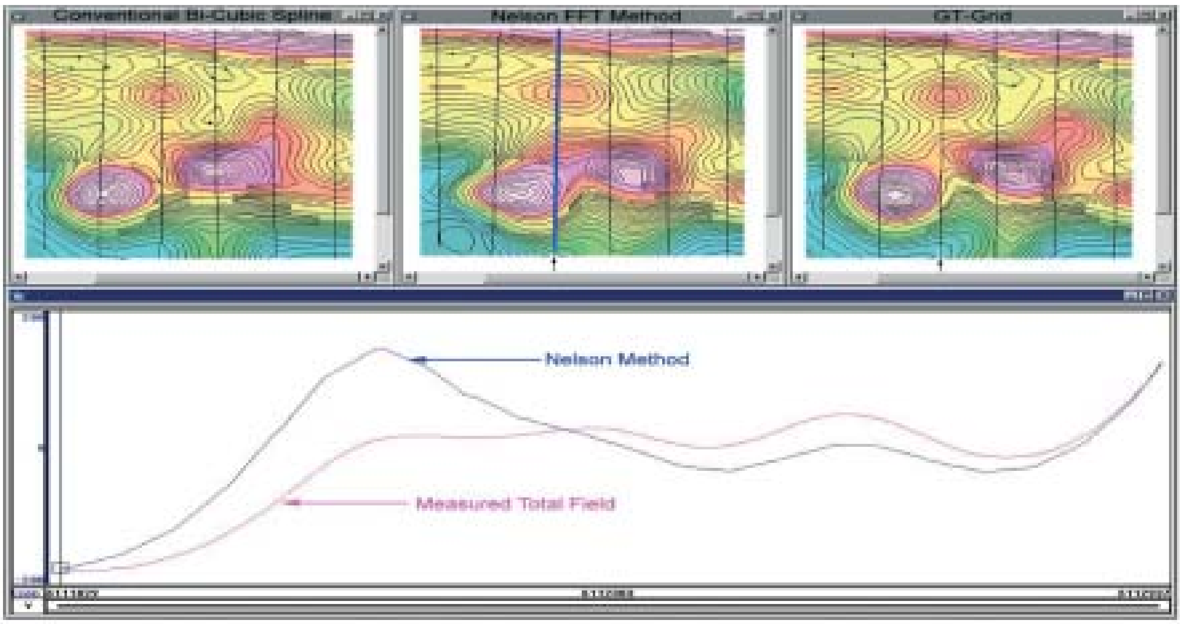

Figure 7 *This illustration presents the total field magnetic map produced by three different methods; a conventional Bi-Cubic spline, the integration of horizontal gradients (Nelson-Nabighian) and the GT-Grid process. Note how the gradient information of the second two methods displaces the circular anomaly in the bottom left corner of the map to a position between flight lines. The profile in the bottom panel presents the total field profile as measured together with that extracted from the Nelson grid. The details and amplitude from the integration process are not always in accordance with measured total field. The Bi-Cubic and GT-Grid maps are in full agreement with the total field profile.*

Nabigian. Gradients can always be calculated from total field and the reverse is also true, except for the DC or static component, hence the use of the word pseudo. Brad Nelson at the NRC presented an idea for reconstructing total field by combining this pseudo total field with a filtered approximation of the regional total field. His concept, designed to solve a severe diurnal interference problem, is being applied by some as a general-purpose magnetic mapping method. For brevity in the following discussion the Nelson-Nabighian method is simply referred to as the Nelson method.

The Nelson horizontal gradient integration process begins with the transformation of measured longitudinal and transverse gradients into east and north components. Each can be levelled by a variety of simple means and individually gridded. The two grids are then combined in the Fourier frequency domain to create a pseudo total field. The pseudo total field has some advantages over a conventional total field map. One is that small anomalies that occur between flight lines are more correctly positioned on the map. The second is that narrow trends, at shallow angle to the flight line direction are more simply and properly depicted. A third is that diurnal variation is excluded from the process. The shortcoming of the technique is that linear features, near parallel to the flight line direction are lost and the amplitude of total field anomalies as depicted may be significantly different than those measured directly.

A different approach to using the horizontal gradient has been developed by Scott Hogg and Associates, called the GT or Gradient Tensor technique. The method uses the measured gradients and total field, in profile form, while creating the total field grid. The measured gradients at any point along a flight line can be used to calculate the direction of maximum change, which is up-slope towards the anomaly peak. Perpendicular to this is the direction of zero change, which defines the direction a contour must follow when crossing the flight line. The GT-Grid process uses both the total field and directional information to build the grid from the profile data.

A conventional gridding process is constrained on by a single parameter, the total field. The Nelson-Nabigian integration process of integrating the horizontal gradient is constrained by two parameters; the two measured gradients. The GT-Grid technique is constrained by three - the two gradients plus the total field. The result is a total field grid that is consistent with measured total field and the measured gradients. Like the Nelson-Nabighian technique it can properly locate anomalies between flight lines but in addition it can render anomalies parallel to the flight line direction, correctly present long wavelength regional variation and ensure that the amplitudes of all total field anomalies are in agreement with the total field as measured. It also ensures that all anomalies, whether indicated on the total field pro-

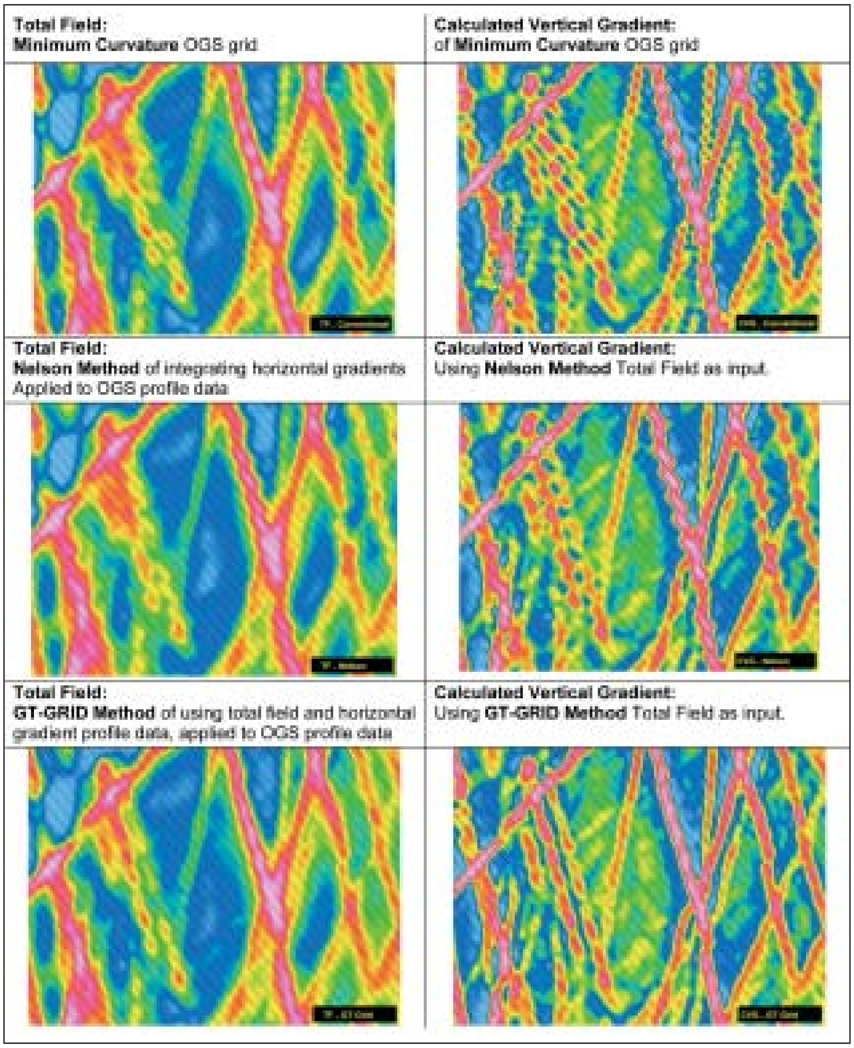

Figure 8 *A demonstration of three gridding techniques using the Ontario Geological Survey (OGS) Kapuskasing-Chapleau aeromagnetic survey data, with measured horizontal gradients. The profile data is identical for each map, only the gridding method is changed. The vertical gradient was calculated in identical fashion from each total field.*

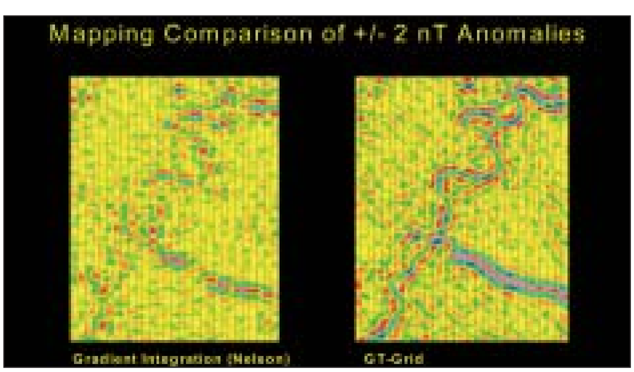

Figure 9 *Comparison of gridding techniques with low amplitude anomalies.*

file, gradient profiles, or both, are reflected in a single, true total field map representation. Figure 7 presents a comparison of methods.

The illustration in Figure 8 is based on the OGS Kapuskasing-Hearst ERLIS data. Goldak Airborne Geophysics recorded horizontal gradient over part of the area. Conventional total field and calculated vertical derivative maps were provided in the open file. The available gradient data allows comparisons to be made of the different mapping techniques. In this example are three total field maps: the first was created by a minimum curvature method, the second was created by the Nelson horizontal gradient integration technique, and the third by the GT-Grid process.

A calculated vertical gradient presentation that serves to highlight the differences has been calculated in the same fashion for each type. In all the maps, trends that are perpendicular to the line direction are well rendered. As the trend direction becomes more closely aligned with the flight direction, the conventional map quickly deteriorates into a disconnected, beads-on-a-string, pattern not evident on the other maps. As the trend direction becomes even more aligned with the flight line direction, the GT-Grid process continues to clearly present the dykes while the clarity of Nelson method representation begins to deteriorate. The map quality based on three independent measured parameter is clearly better than that based on one or two.

Although the magnetic gradients and total field measurements use the same magnetometers, the resolution of the total field and gradient measurements are not the same. In Figure 9, the map created by the GT-Grid method clearly presents a sinuous magnetic anomaly. It is only about +/-2 nT in amplitude and is due to a river channel cutting through glacial till. The horizontal gradients from this anomaly are near the measurement threshold of the horizontal gradiometer and the anomaly is poorly rendered by the Nelson technique using gradients alone. This emphasizes the fact that gradient measurements should be used as supplementary information, not an alternative to total field measurement.

Summary

Measured vertical gradient can be used to correct for terrain clearance variation and this simple correction deserves more routine use as part of a standard magnetic compilation process. Horizontal gradients combined with the Nelson technique provide a means to deal with excessive diurnal interference as well as some improvements to map resolution. If diurnal interference is not excessive, the GT-Grid process can use the gradient data to improve both map resolution and accuracy.

Measured magnetic gradients do provide useful information and are a valuable addition to any aeromagnetic survey. The gradient systems and processing techniques currently available have already made a significant impact that will likely redefine the aeromagnetic standards and expectations of the future.

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